LOCA RESEARCH RESULTS FOR HIGH-BURNUP BWR FUEL

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HIGH BURNUP LOCA FEATURES

- **BWR Fuel Rods (Limerick at ≈57 GWd/MTU, ≈10 μm OD Oxide)**
  - Effect of tight fuel-cladding bond and restricted gas flow on ballooning, burst, inner-surface-oxidation/hydrogen-pickup
  - Effect of irradiation on high temperature oxidation in steam
  - Effect of fuel-cladding mechanical interaction on fragmentation resistance during water quench; post-quench ductility

- **PWR Fuel Rods (HBR at ≈67 GWd/MTU, ≤ 100 μm OD Oxide)**
  - Similar fuel-cladding issues as for BWR
  - Effect of in-reactor oxide layer on oxidation kinetics and ECR.
  - Effect of hydrogen pickup on oxidation kinetics, fragmentation-resistance during water quench and post-quench ductility.

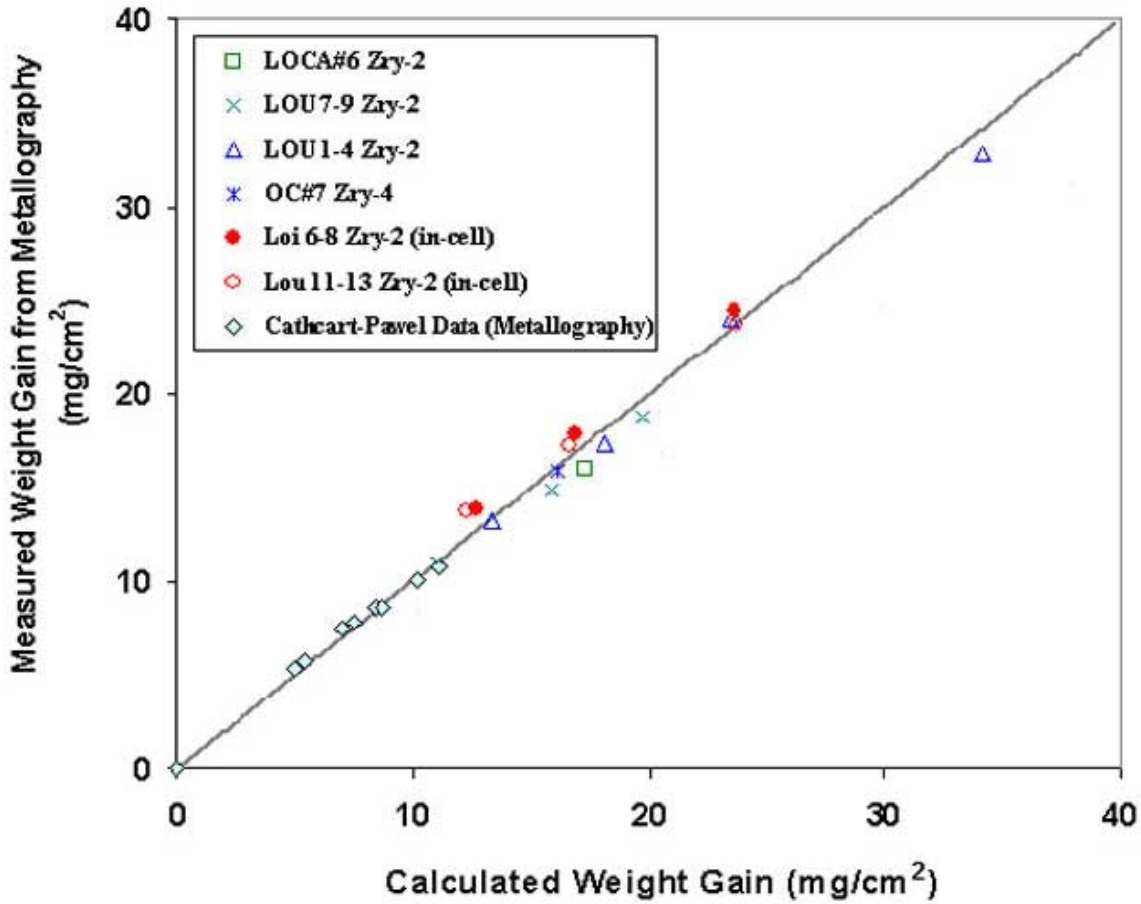
ANL LOCA-RELEVANT TESTS FOR HIGH BURNUP FUEL CLADDING

- **Steam Oxidation Kinetics Studies**
  - 900-1300°C, emphasis on **1204°C** for 5-20 minutes
  - Kinetics of weight gain, (oxide + α) layer growth rate, effective β layer thickness vs. time at temperature, ECR
- **LOCA Integral Tests**
  - Test adequacy of 10CFR50.46 ECCS licensing criteria (**ECR ≤ 17%, T ≤ 1204°C**) for high burnup fuel
  - Determine ECR (≥17%) thresholds for thermal quench fragmentation and loss of post-quench ductility
- **Post-Quench Ductility Tests (Bend & Ring Compress.)**

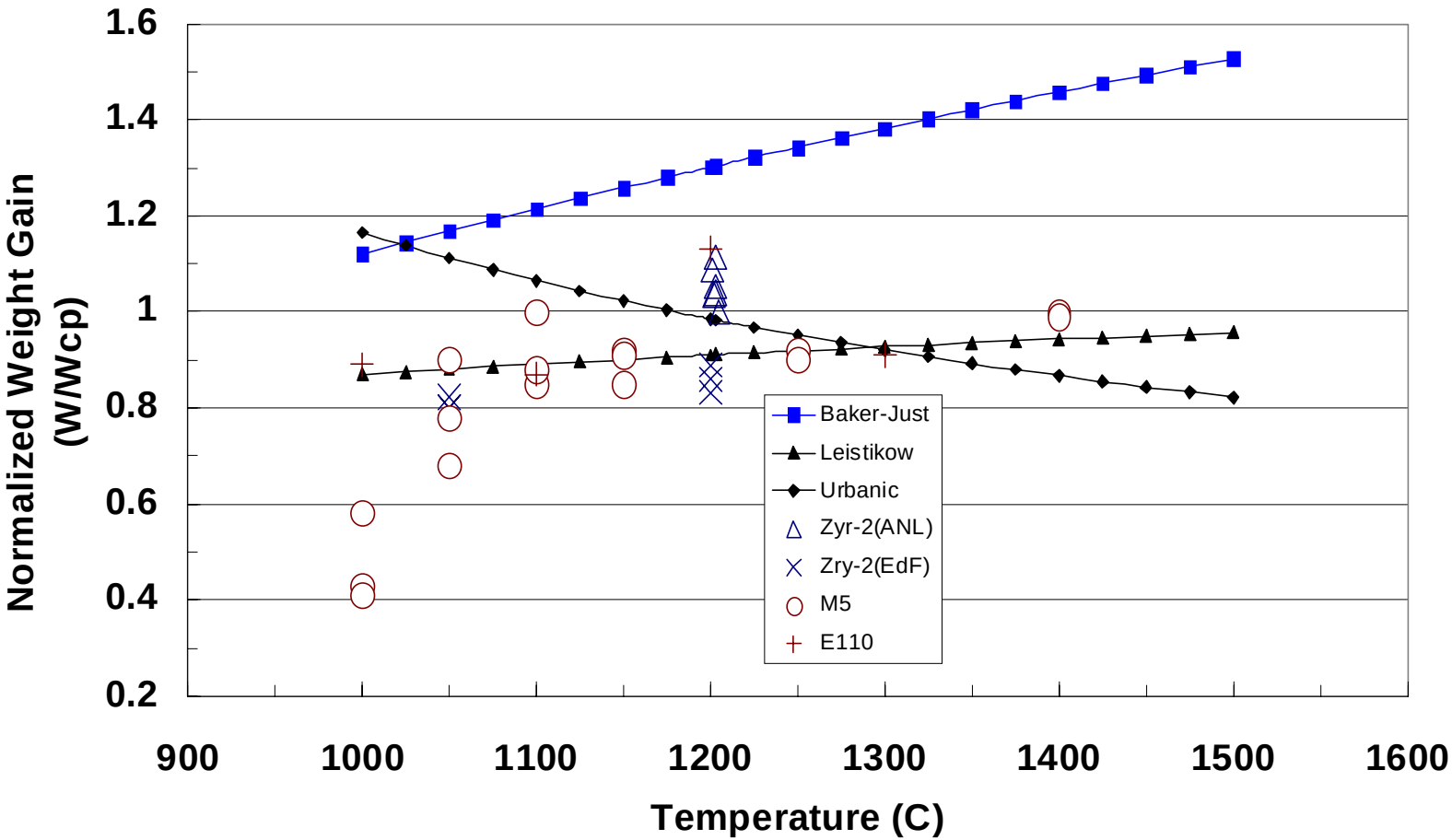
SUMMARY OF STEAM OXIDATION KINETICS RESULTS

- **Metallographic Results for 1200°C Tests**
  - No significant difference in measured weight gain (Δw_m) for unirradiated and irradiated (10-μm pre-test oxide layer) Zry-2 and unirradiated Zry-4
  - Excellent agreement between Δw_m and Cathcart-Pawel (CP) model predictions (Δw_p)
  - CP Δw_p is adequate "best-estimate" correlation for Zry-2, Zry-4, ZIRLO, M5 and E110 at 1100-1500°C
- **Metallographic Analysis for 1000, 1100 and Duplicate 1200°C Test Samples (in progress)**

Measured Weight Gain from Metallography for Irradiated and Unirradiated Zry-2 and Zry-4



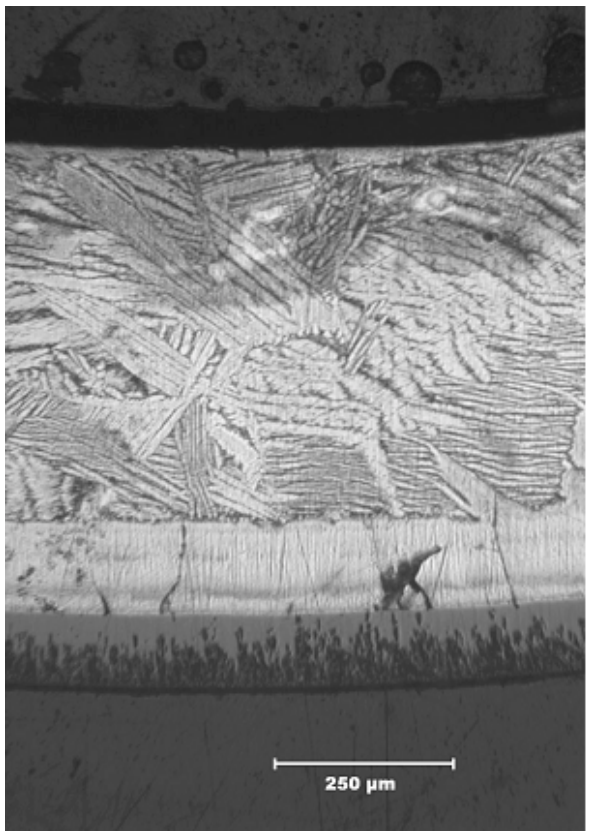
Comparison of Weight Gain Correlations and Data Normalized to the Cathcart-Pawel Correlation

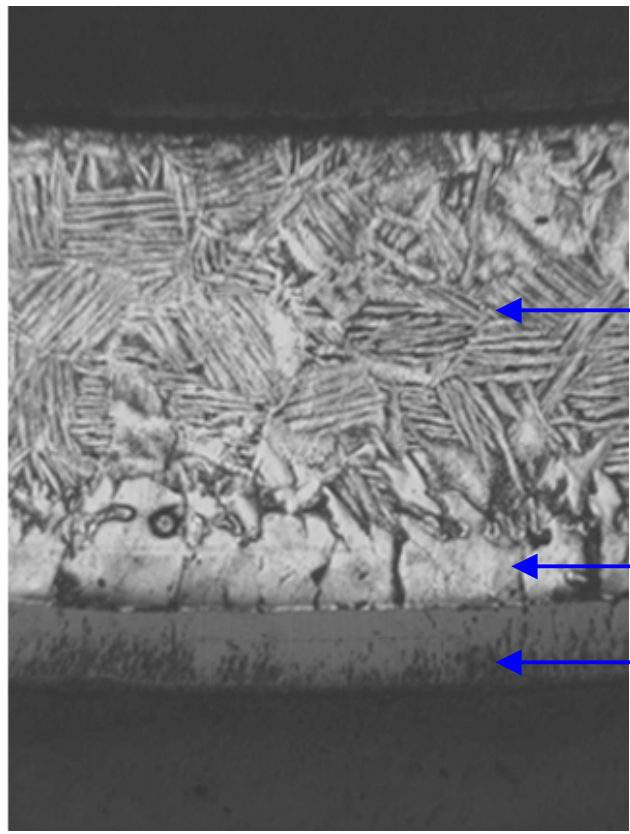


SUMMARY OF STEAM OXIDATION KINETICS RESULTS (Cont'd)

- **Assessment of Cathcart-Pawel (CP) Models**
  - Based on very rapid heating and cooling rate test data
  - Weight gain correlation is good even for slow ramp rates
  - Underpredicts α-layer and overpredicts β-layer thickness for LOCA-relevant cooling rates (1-8°C/s) due to oxygen diffusion from β to α phase during 1200°C → 800°C
  - ANL results (-5°C/s): 25% higher (oxide + α) than CP
  - Impact is TBD as "ductility" increases with reduction in oxygen and decreases with thickness reduction of β layer

Oxide, α and β Layer Characteristics (in Steam at 1204°C for 10 Minutes; ECR = 11%)





unirradiated Zry-2 **irradiated Zry-2**

LOCA INTEGRAL TESTING SCOPE

- **Parameters Common to BWR and PWR Tests**
  - Fuel-cladding samples = 305-mm long; fueled region = 270 mm
  - **PCT = 1204±20°C**, temperature ramps relevant to SB-LB LOCA
  - Internal pressure P_i <1.3×system pressure, **plenum V ≈ 10 cm^3**
  - Best-estimate **13% ≤ ECR < ≈30%** → oxidation time ≈1-10 min.
- **High Burnup BWR Rods (Limerick)**
  - **Temperature ramp rate = 5°C/s** (2.5-7°C/s for SB-to-LB LOCA)
  - Cladding **$\Delta P = P_i - P_s \leq 8.6$ MPa** [6.7 MPa (SB)- 8.6 MPa (LB)]
- **High Burnup PWR Rods (H. B. Robinson)**
  - Temperature ramp rate = 5°C/s (1-2°C/s for SB, 7-10°C/s for LB)
  - Cladding $\Delta P = P_i - P_s < 20$ MPa [$P_s = 3.4 \rightarrow 0.2$ MPa (SB → LB)]

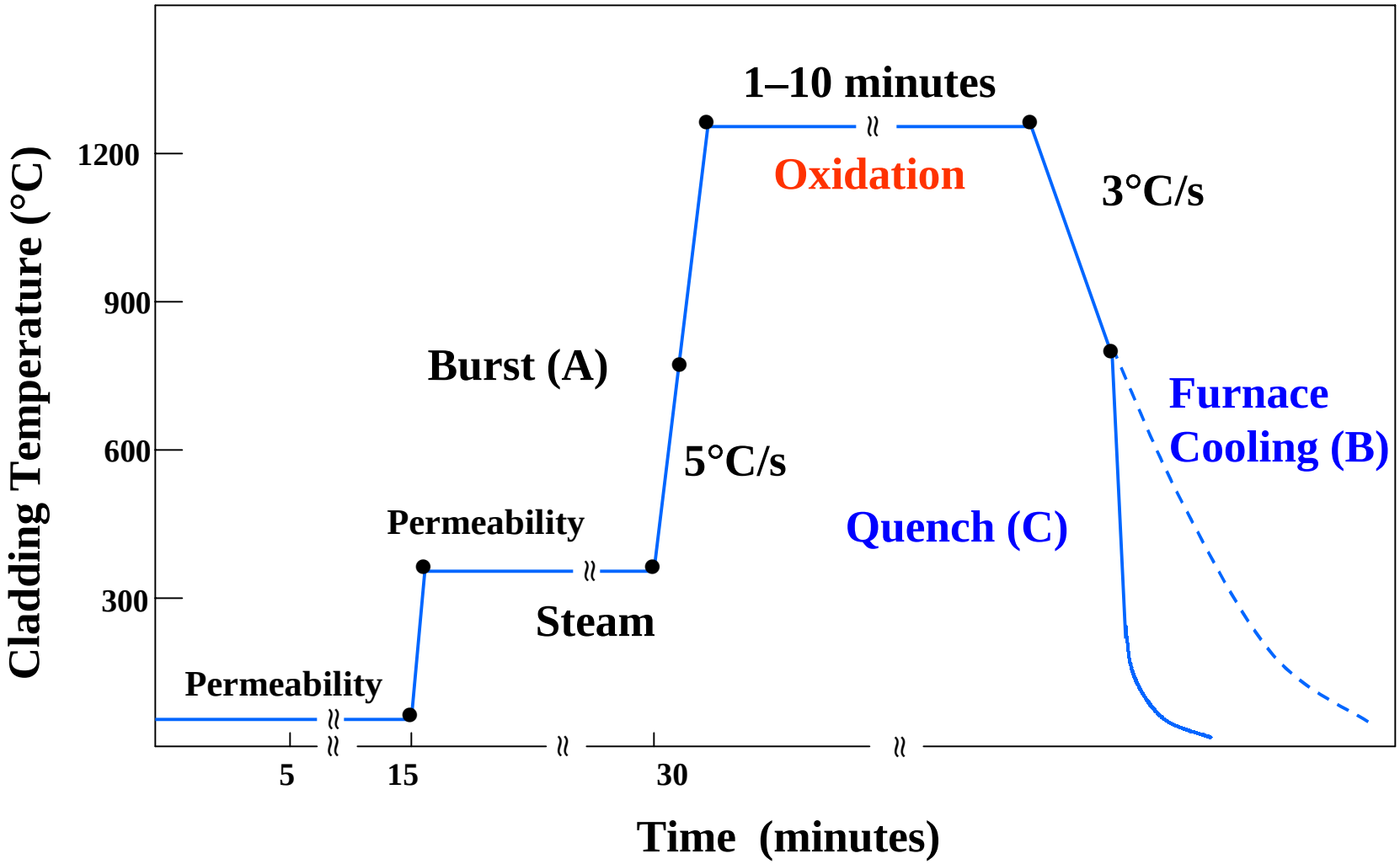
LOCA INTEGRAL TESTING SCOPE (Continued)

- **Steam and Quench Water Flow-rates/Volume**
  - Steam flow = 5-10 g/minute
  - **Cool-down rate = 3°C/s from 1204°C to 800°C** (1-8°C/s for BWR)
  - Quench water velocity = 5 mm/s (initiated at 800°C)
- **Test Times at 1204°C**
  - Maximum ECR depends on wall thinning and extent of double-sided oxidation
  - **Five-minute hold-time at 1204°C for 1st set of tests**
  - **Expected ECR ≤ 21% (23% CP, 30% BJ)**

LOCA INTEGRAL TEST SEQUENCE FOR FIRST SERIES OF BWR TESTS

- **Phase A: Fuel Permeability, Ballooning and Burst**
  - Permeability at 30°C and 300°C
  - Ramp (5°C/s) to burst in high purity argon
  - Slow furnace cool from burst temperature
- **Phase B: Above Plus Oxidation**
  - Permeability (30°C and 300°C); ramp to 1204°C in steam
  - Hold (5 min.) at 1204°C; cool to 800°C at 3°C/s
  - Slow furnace cool from 800°C to RT
- **Phase C: Above Plus Quench at 800°C**
  - Repeat B through cooling to 800°C; quench at 800°C

LOCA INTEGRAL TEST SEQUENCE

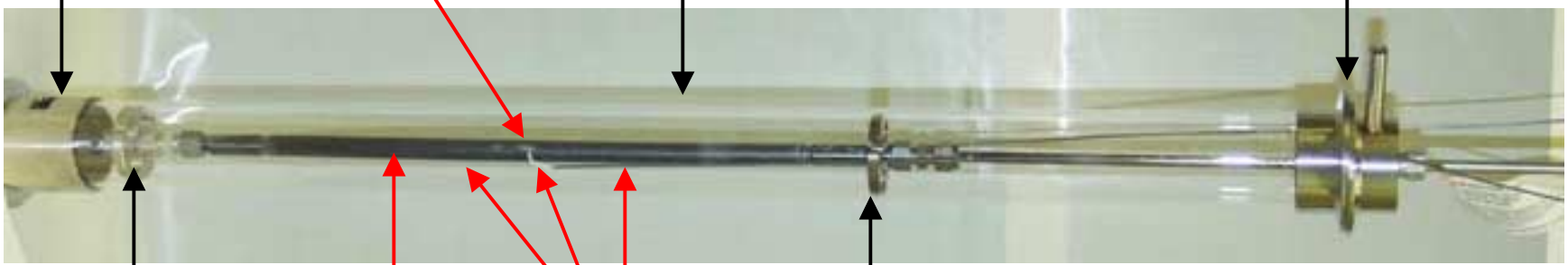


LOCA INTEGRAL TEST APPARATUS

- **Out-of-Cell LOCA Integral Test Apparatus**
  - Same design as in-cell apparatus (completed)
  - Baseline data for unirradiated, archival cladding (Zry-2 completed)
  - Modifications of in-cell apparatus (ongoing)
  - Oxidation and LOCA Integral tests of cladding alloys (ongoing)
- **In-cell LOCA Integral Test Apparatus**
  - Same design and control system (shared) as out-of-cell apparatus
  - **All components are in-cell except quench unit**
  - **Limerick Phase A Test (completed 8-15-02)**
  - **Limerick Phase B Test (completed 9-23-02)**
  - Full LOCA Integral Test with Limerick sample (Jan. 2003)
  - H.B. Robinson PWR tests will follow Limerick BWR tests

Out-of-Cell LOCA/Oxidation system

LOCA TEST TRAIN ASSEMBLY



SUMMARY OF OUT-OF-CELL LOCA INTEGRAL TEST RESULTS

- **Test Specimens and Conditions**

  - Specimens: GE-11 (9×9) **Zry-2** cladding (**0.71-mm wall**), zirconia pellets with 0.1-mm radial gap, 10-cm^3 void volume above pellets; Limerick archive cladding

  - Conditions: cladding ΔP = 8.62 MPa at RT

- **Test #3 Results (10 min. in steam at 1204°C)**
  - Peak ΔP = 9.31 MPa, burst $\Delta P \approx$ 8.41 MPa, **burst T ≈ 760°C**
  - "Dog-bone-shaped" burst opening; ≈13-mm long (**ECR = 29%**)
  - **Peak $\Delta D/Do \approx 60\%$**; axial extent of balloon ≤130 mm
  - Specimen survived thermal quench & post-quench handling

SUMMARY OF OUT-OF-CELL LOCA INTEGRAL TEST RESULTS (Cont'd)

- **Test #4 Results (10 min. in steam at 1204°C)**
  - Peak ΔP = 10.28 MPa, burst ΔP ≈ 9.42 MPa, **burst T ≈ 720°C**
  - Similar burst opening and ballooning strain as in Test #3
  - **Sample failed across mid-burst region at 100°C after quench**
  - Based on results, hold time at 1204°C should be < 10 min.
- **Test #5 Results (ramped to burst in Ar)**
  - Peak ΔP = 8.95 MPa, burst ΔP ≈ 8.61 MPa, **burst T ≈ 732°C**
  - "Dog-bone-shaped" burst opening; ≈13-mm long; 2-mm wide
  - **Peak ΔD/Do ≈ 44%**; axial extent of balloon ≈100-mm long

Out-Cell LOCA (OCL) Test 3: 10 min. at 1204˚C
(Survived quench & post-quench handling)

2850 wppm H_2

2250 wppm H_2

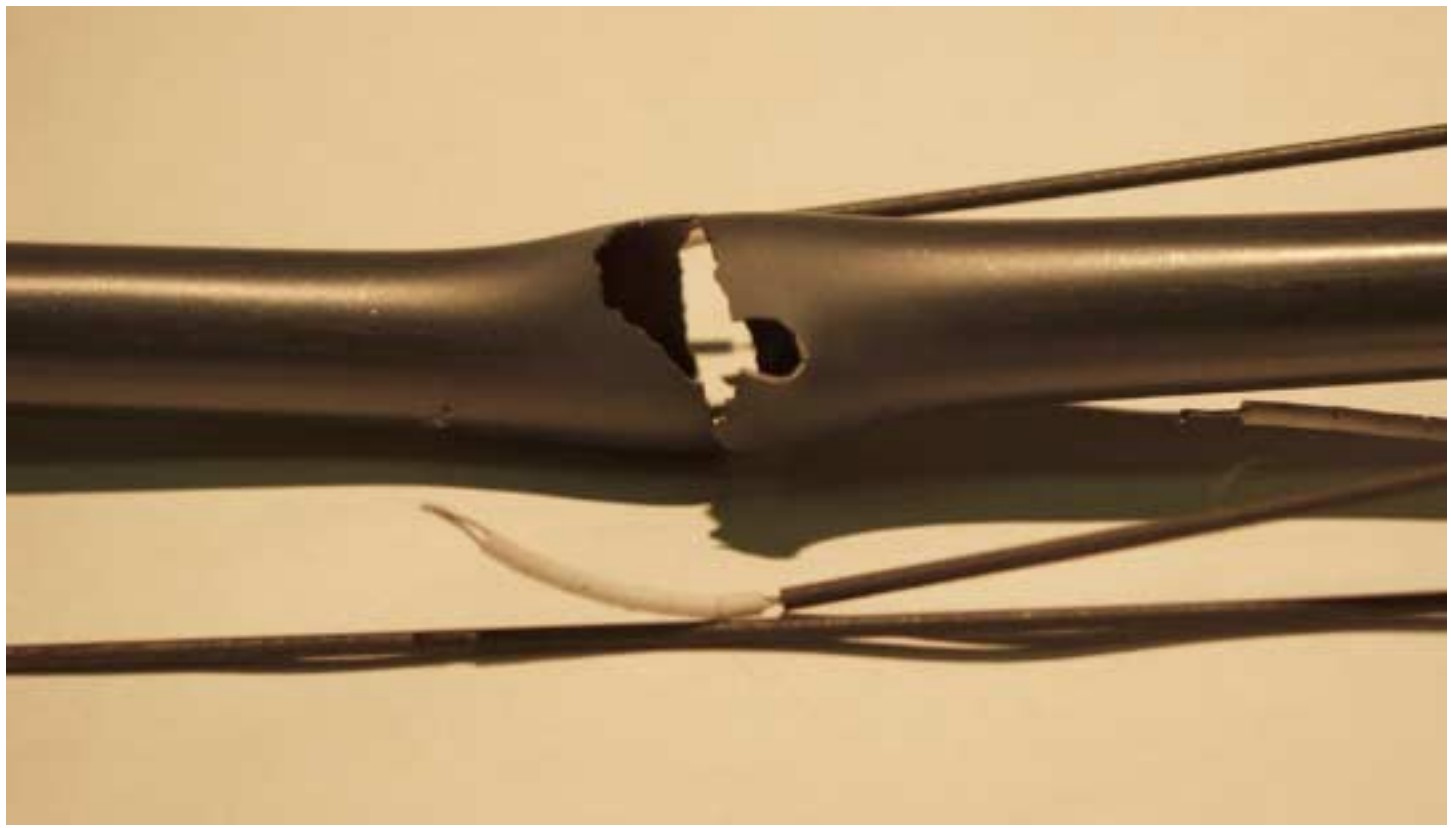
1250 wppm H_2

12% ECR

21% ECR

29% ECR

Out-of-cell Test 4: 10 min. at 1204˚C, C-P ECR ≈ 30%
(Survived quench; fractured at 100˚C under dead-weight load)



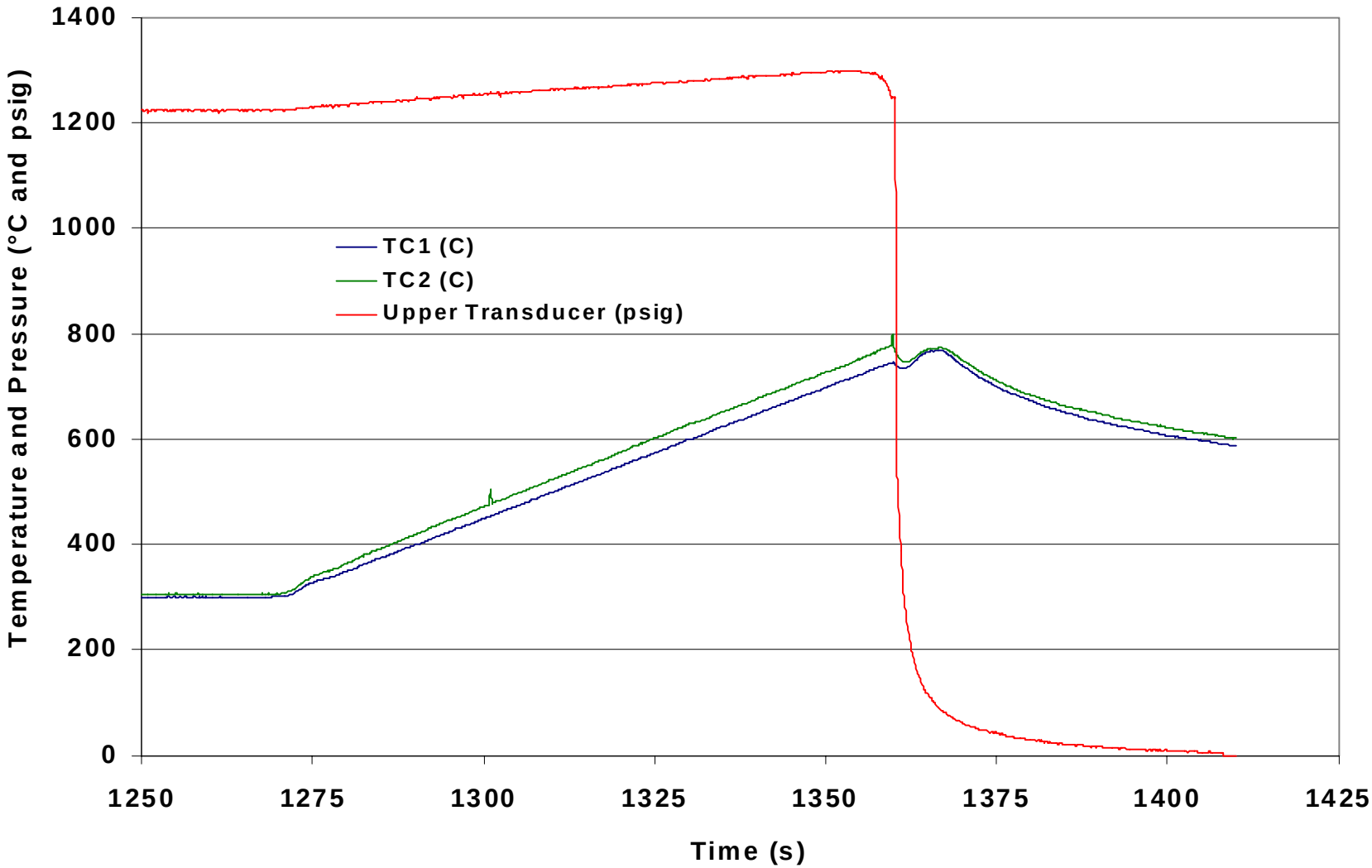
1st LOCA INTEGRAL TEST RESULTS LIMERICK HIGH-BURNUP BWR PHASE A

- **Limerick Specimens Prepared**
  - **Phase A: middle of Grid Span #6; 0.94-1.24 m above fuel MP**
  - Phase B: middle of Grid Span #5; 0.46-0.76 m above fuel MP
  - Phase C: to be prepared from GS #5 & 6 of different rod
- **Phase A Test (Completed on 08-15-02)**
  - Calibration of top pressure transducer at RT from 0-10 MPa
  - Pressurize top of specimen with He to 8.38 MPa at 300°C
  - Stabilize (pressure rose to 8.56 MPa over 15 min) at 300°C
  - **Ramp temperature to burst in Ar; slow furnace cool**

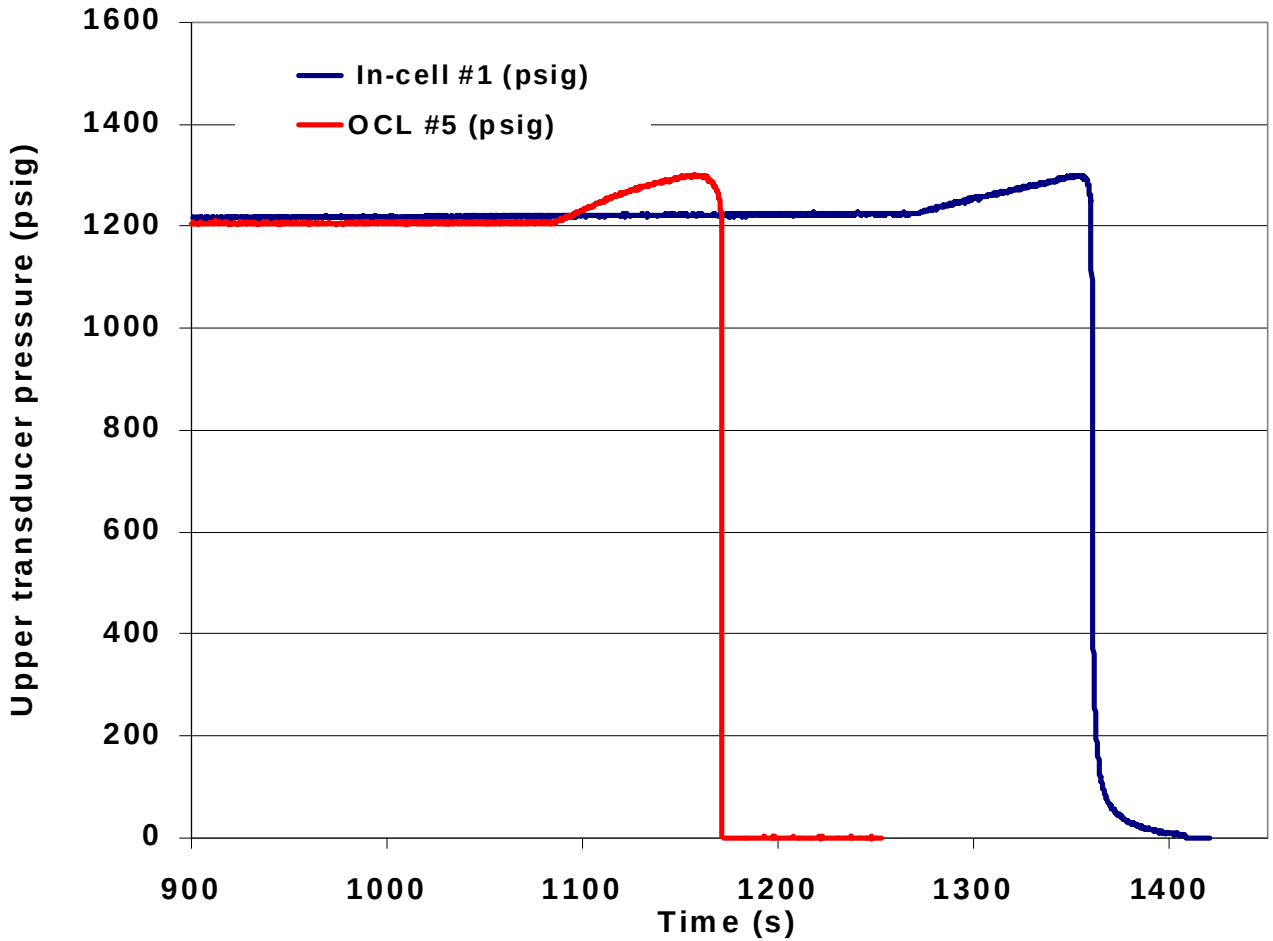
1st LOCA INTEGRAL TEST RESULTS LIMERICK HIGH-BURNUP BWR PHASE A (Cont'd)

- **Burst Conditions for Phase A vs. OCL#5**
- **Peak ΔP = 8.95 MPa for both tests**
  - Burst $\Delta P \approx 8.61$ MPa at 755°C (≈8.26 MPa at 732°C for OCT#5)
  - **Burst opening is oval (dog-bone for OCL#5)**
  - Burst length (≈12-13 mm) and max. opening (2-3 mm) for both
- **Balloon Characteristics for Phase A vs. OCT#5**
  - Average $\Delta D/D_o$ at burst center = 38% (44% for OCL#5)
  - **Axial extent of ballooning = 50 mm (100 mm for OCL#5)**
  - Note: $\Delta T_\theta \approx 30$°C (≈10°C for OCL#5)

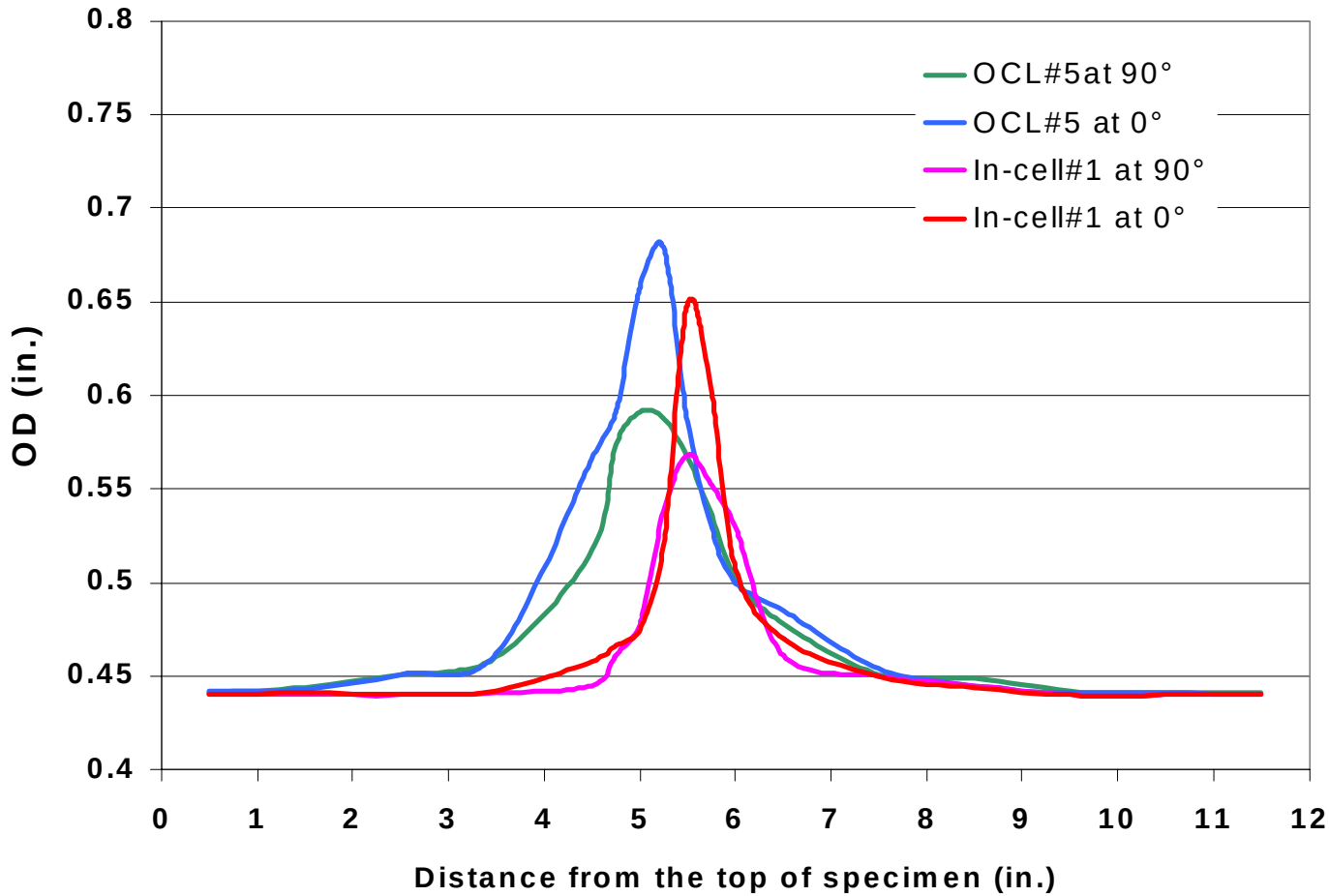
High-Burnup BWR In-cell LOCA Integral Test #1
Fuel Segment Temperature Ramp to Burst (8-15-02)



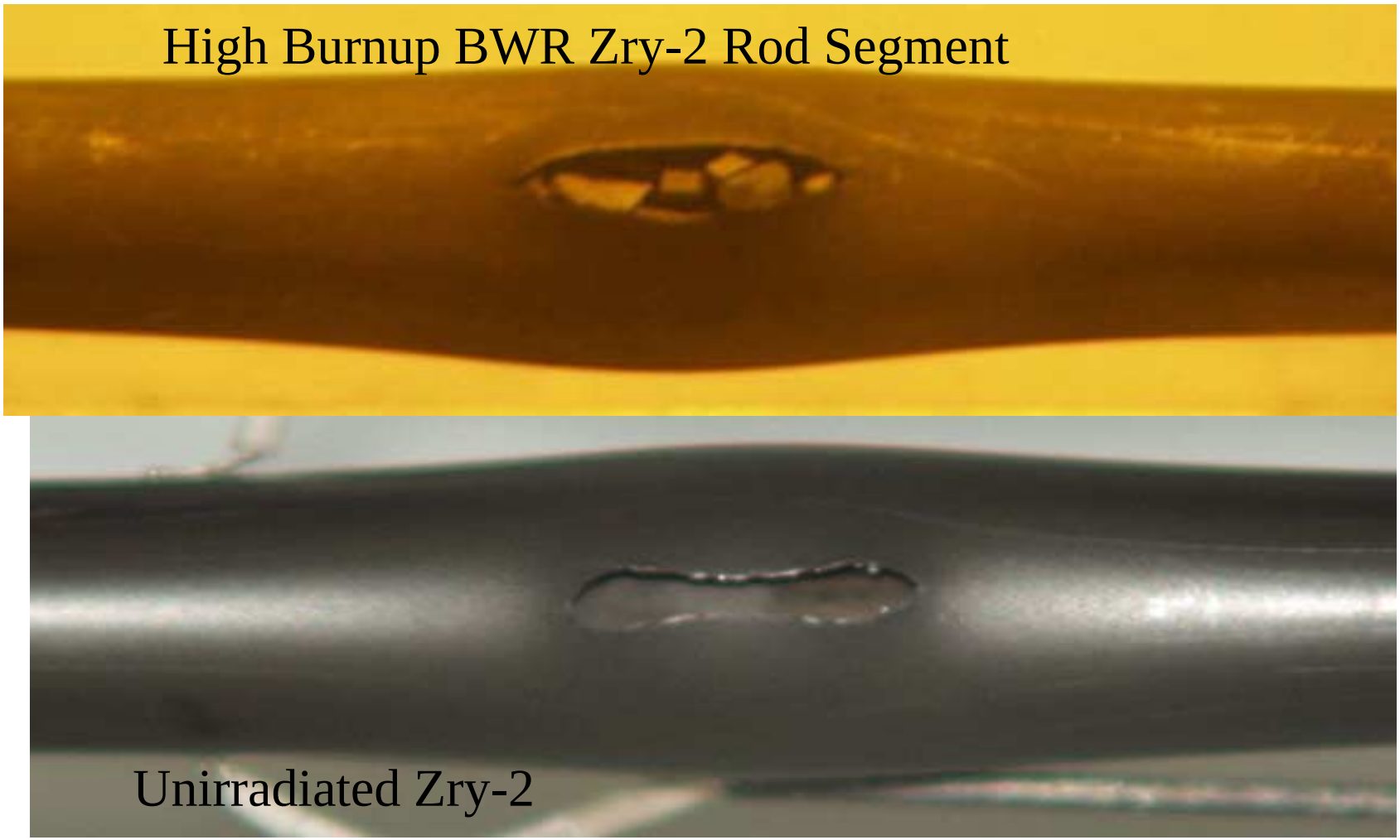
PRESSURE HISTORIES FOR IN-CELL TEST #1 AND OUT-OF-CELL LOCA TEST #5



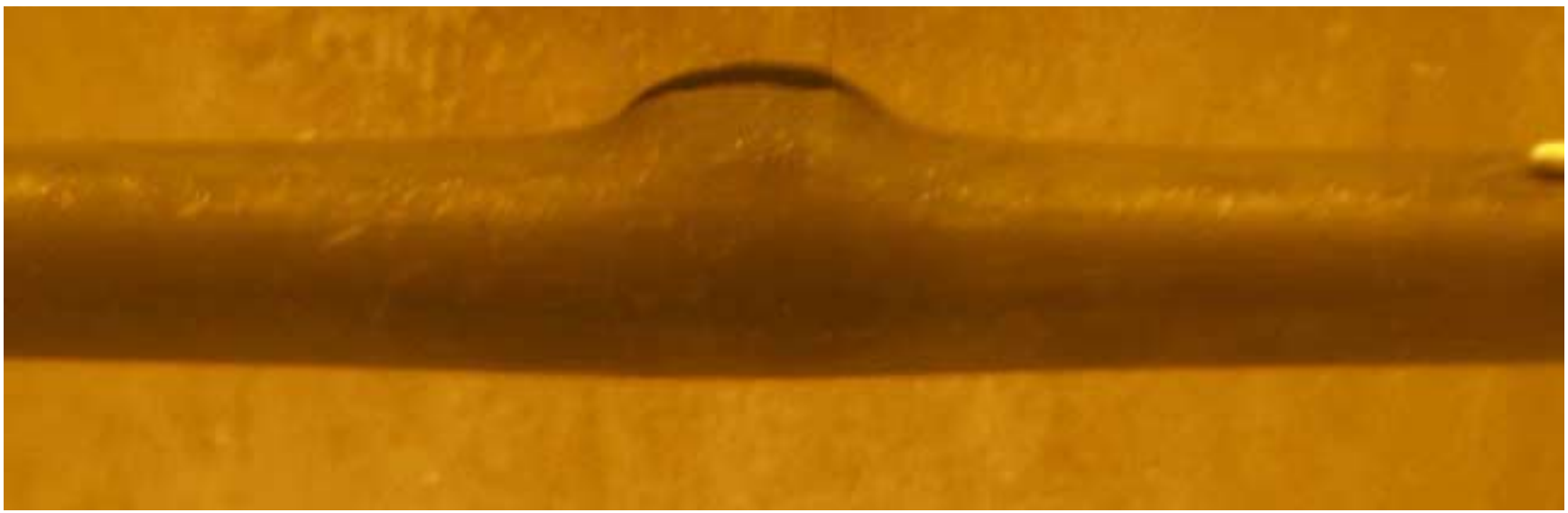
BALLOONING COMPARISON
IN-CELL TEST #1 vs. OUT-OF-CELL TEST#5



BURST OPENING COMPARISON



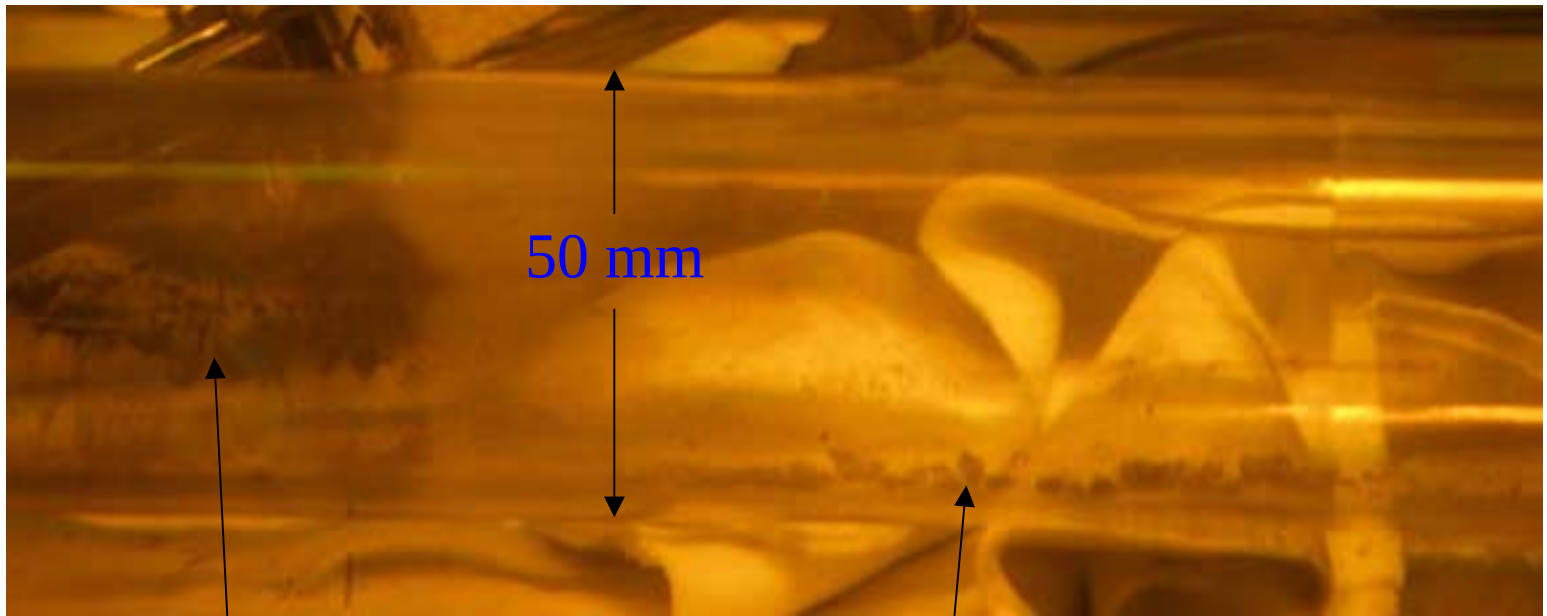
SIDE VIEW OF HIGH-BURNUP BWR ROD SEGMENT AFTER LOCA PHASE A TEST



FUEL BEHAVIOR DURING AND AFTER HIGH-BURNUP BWR LOCA TEST #1

- **Dark Deposit on Quartz Tube (Fading with Time)**
  - Black deposit on tube (will be gamma-scanned, Cs??)
  - Occurred during burst
  - Extends from burst region to about 50 mm above burst
- **Fuel Particle Fallout (5.2 g) during Post-Test Handling**
  - Test train was moved from vertical position in furnace to horizontal position at a different workstation
  - Large number of small fuel particles (<3 mm in diam.) fell out of burst opening during rotation of specimen from vertical to horizontal and about longitudinal axis

FUEL DEPOSIT AND PARTICLES WITHIN QUARTZ TUBE



Black Deposit
Cs Compound??

Fuel Particles
< 3 mm in diameter

2nd LOCA INTEGRAL TEST RESULTS HIGH-BURNUP BWR PHASE B

- **Permeability Results at 30°C**
  - Pressurization ramp at top of specimen to 8.7 MPa

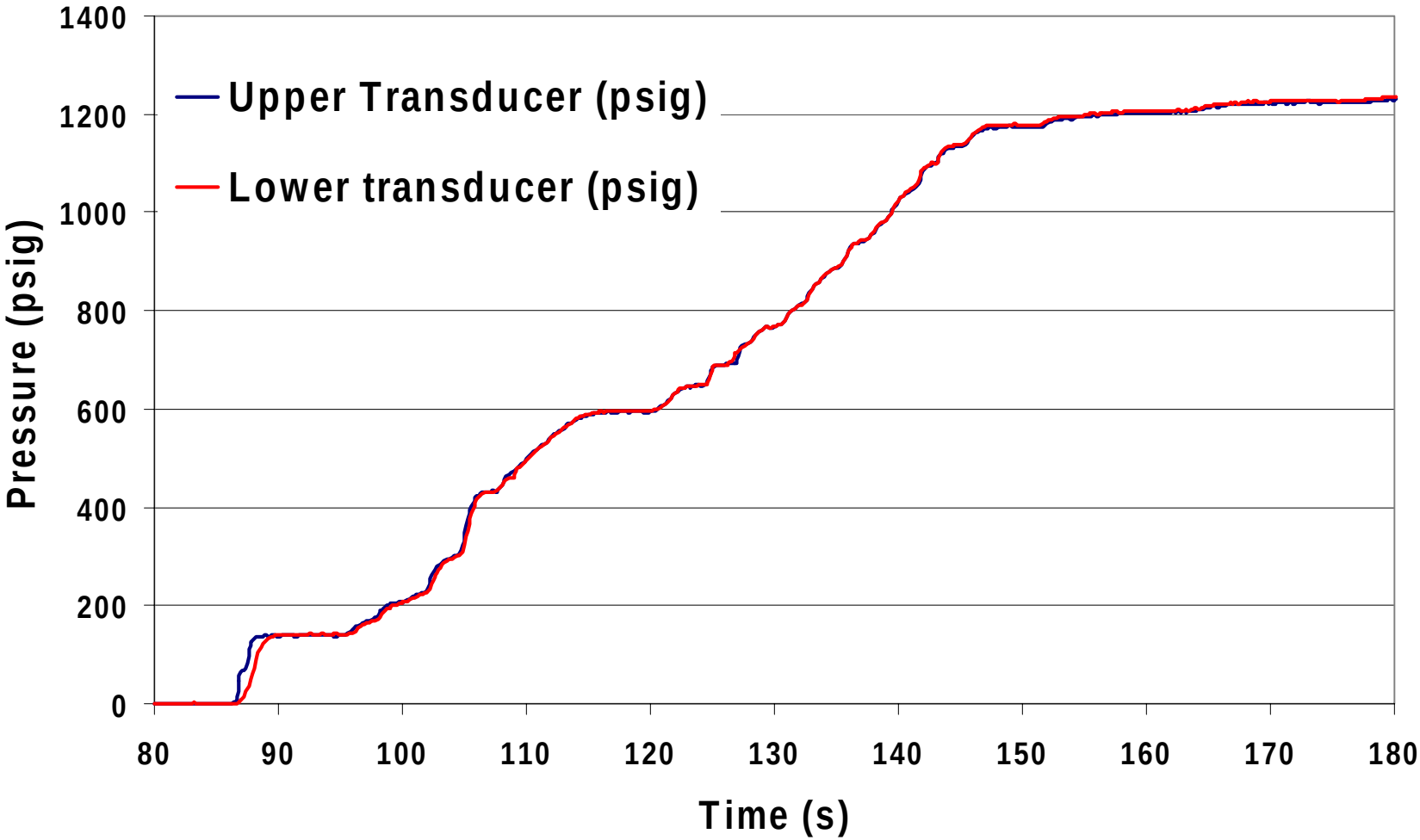
    Excellent gas communication from 1 to 8.7 MPa

    Small axial pressure drop ($\Delta P_z \leq 0.5$ MPa) for 0-4s
  - Rapid pressure release at top of specimen (valve open)

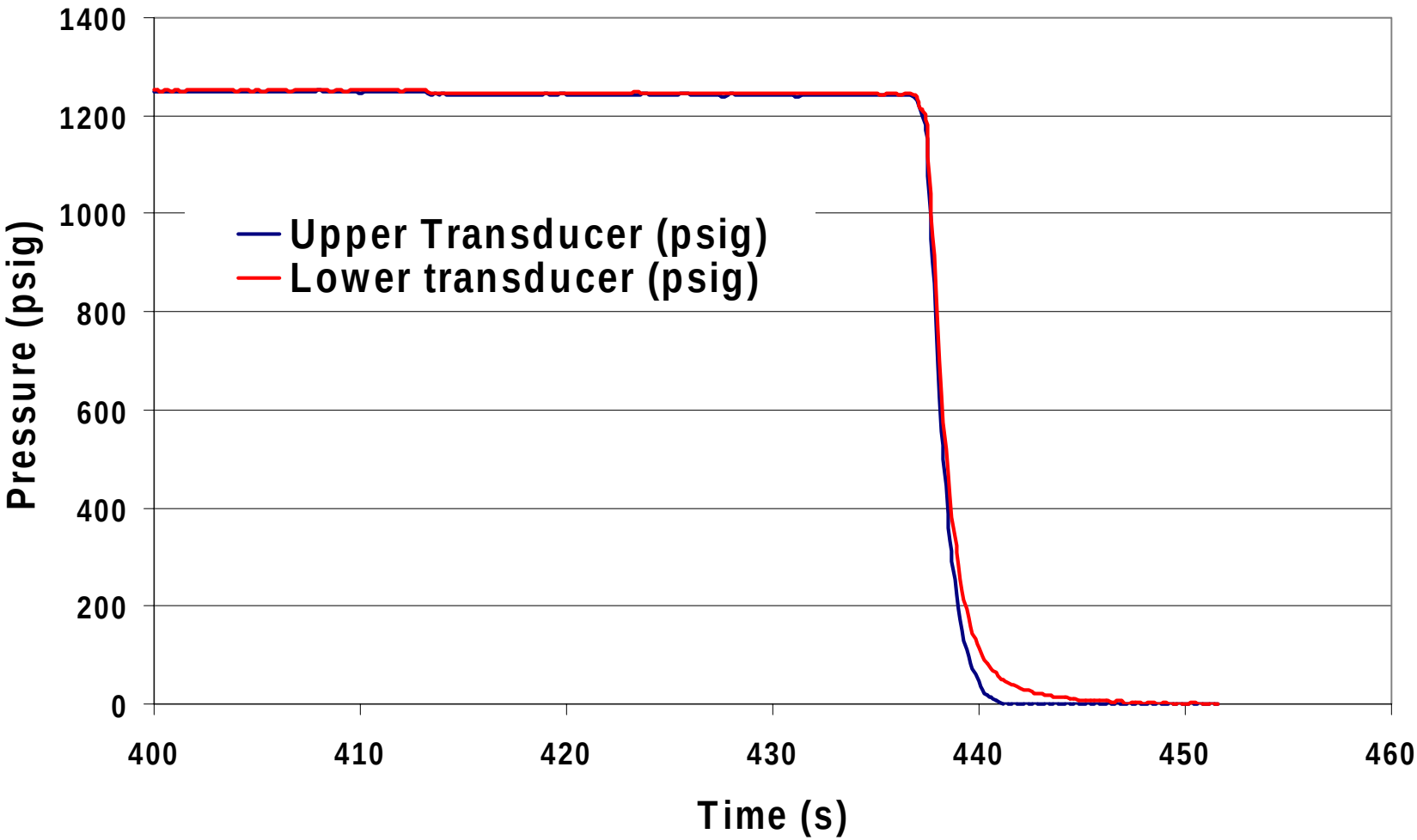
    Lag in lower pressure response ($\Delta P_z \leq 0.6$ MPa)

    Slow release from bottom transducer from 2→0.1 MPa
  - Results are to be consistent with fuel microstructure (macro- and micro-cracks) and high gas release

In-cell LOCA Integral Test #2 with Limerick BWR Fuel
Gas Communication at 30°C during Pressure Rise, 9/19/02

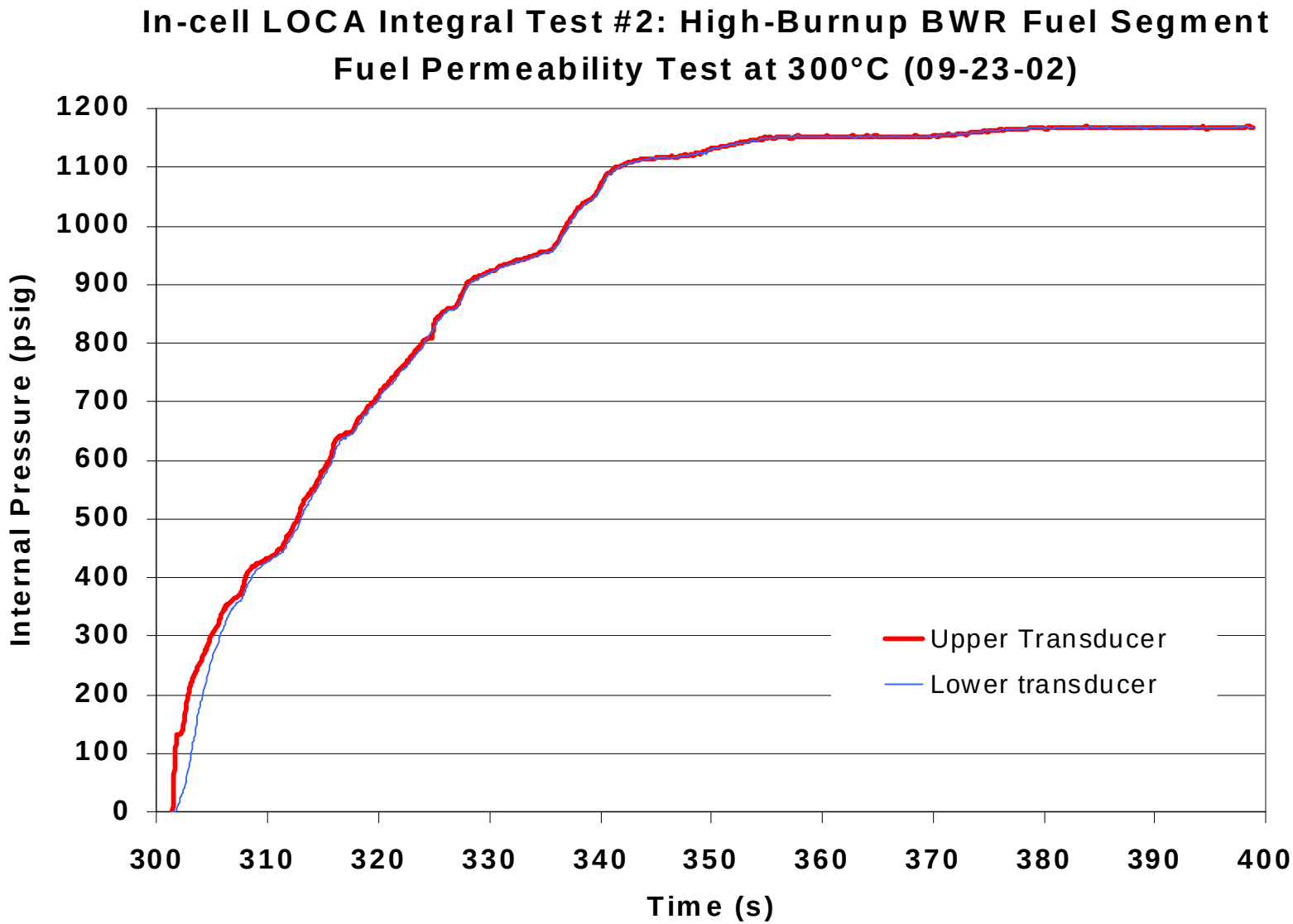


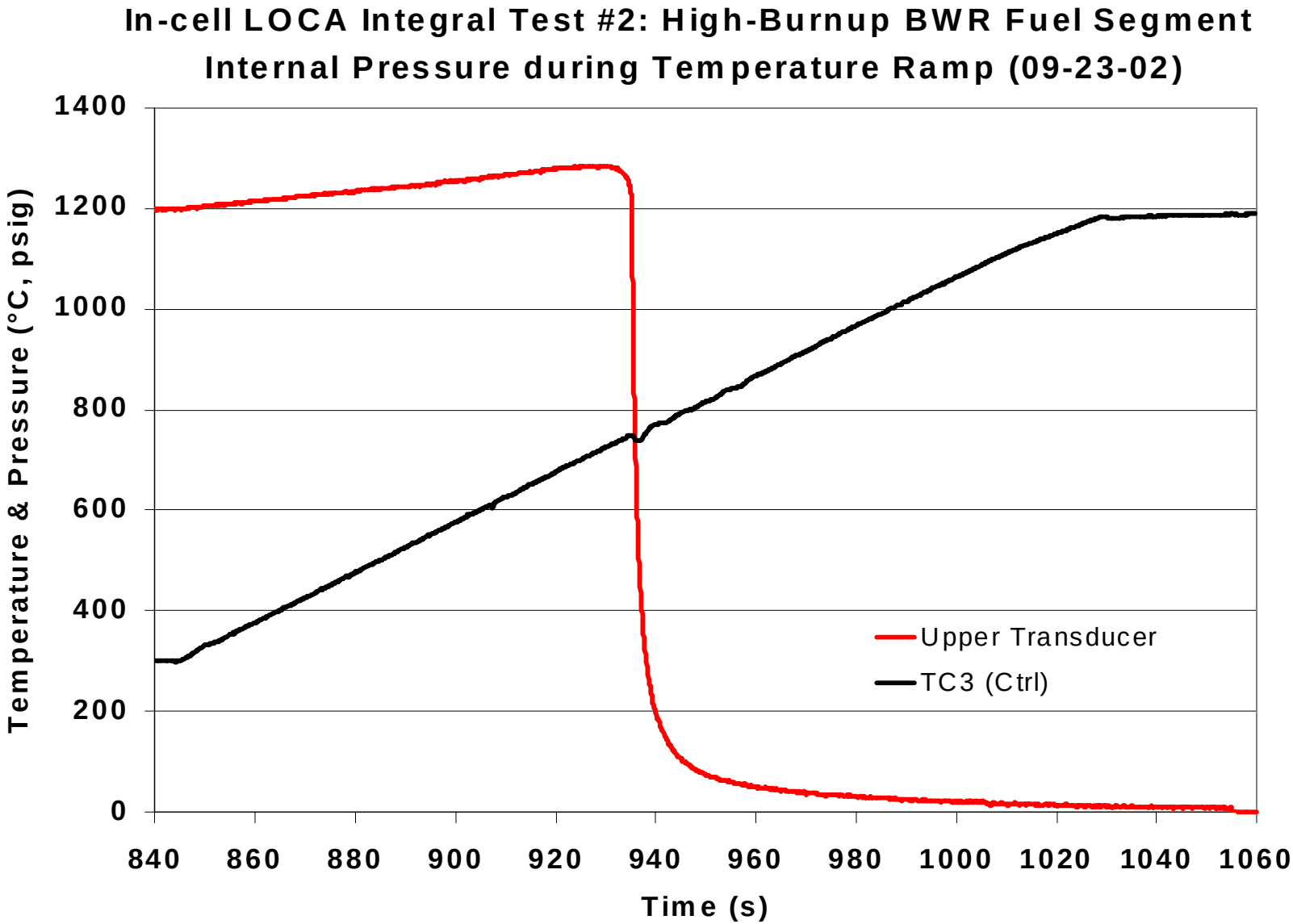
In-cell LOCA Integral Test #2 with Limerick BWR Fuel
Gas Communication at 30°C during Pressure Release, 9/19/02



2nd LOCA INTEGRAL TEST RESULTS HIGH-BURNUP BWR PHASE B (Cont'd)

- **Permeability Results at 300°C**
  - Pressurization ramp at top of specimen to 8.0 MPa
  - **Excellent gas communication from 2 to 8 MPa**
  - Some axial pressure drop ($\Delta P_z \leq 0.9$ MPa) for 0-4s
  - Pressure increases to 8.4 MPa during 300°C hold
- **Temperature Ramp to 1204°C**
  - Pressure peaks at 9.0 MPa at 728°C
  - **Burst at ≈750°C** and ≈8.4 MPa (1200 psig)
  - Rapid drop to 3.5 MPa; slow drop from 3 → 0.1 MPa

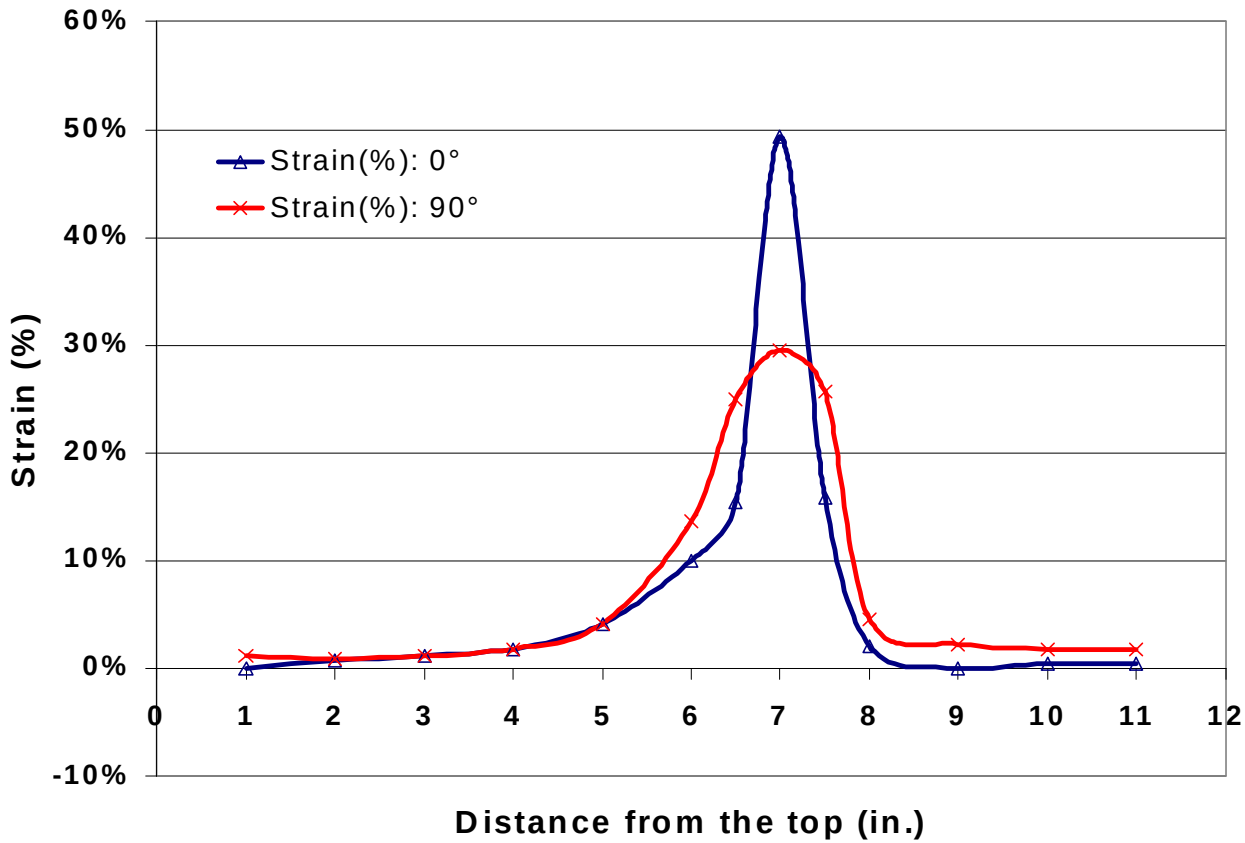

In-cell LOCA Integral Test #2: High-Burnup BWR Fuel Segment
Fuel Permeability Test at 300°C (09-23-02)
Internal Pressure (psig)
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
300
310
320
330
340
350
360
370
380
390
400
Time (s)
Upper Transducer
Lower transducer


In-cell LOCA Integral Test #2: High-Burnup BWR Fuel Segment
Internal Pressure during Temperature Ramp (09-23-02)
Temperature & Pressure (°C, psig)
1400
1200
1000
800
600
400
200
0
840
860
880
900
920
940
960
980
1000
1020
1040
1060
Time (s)
Upper Transducer
TC3 (Ctrl)

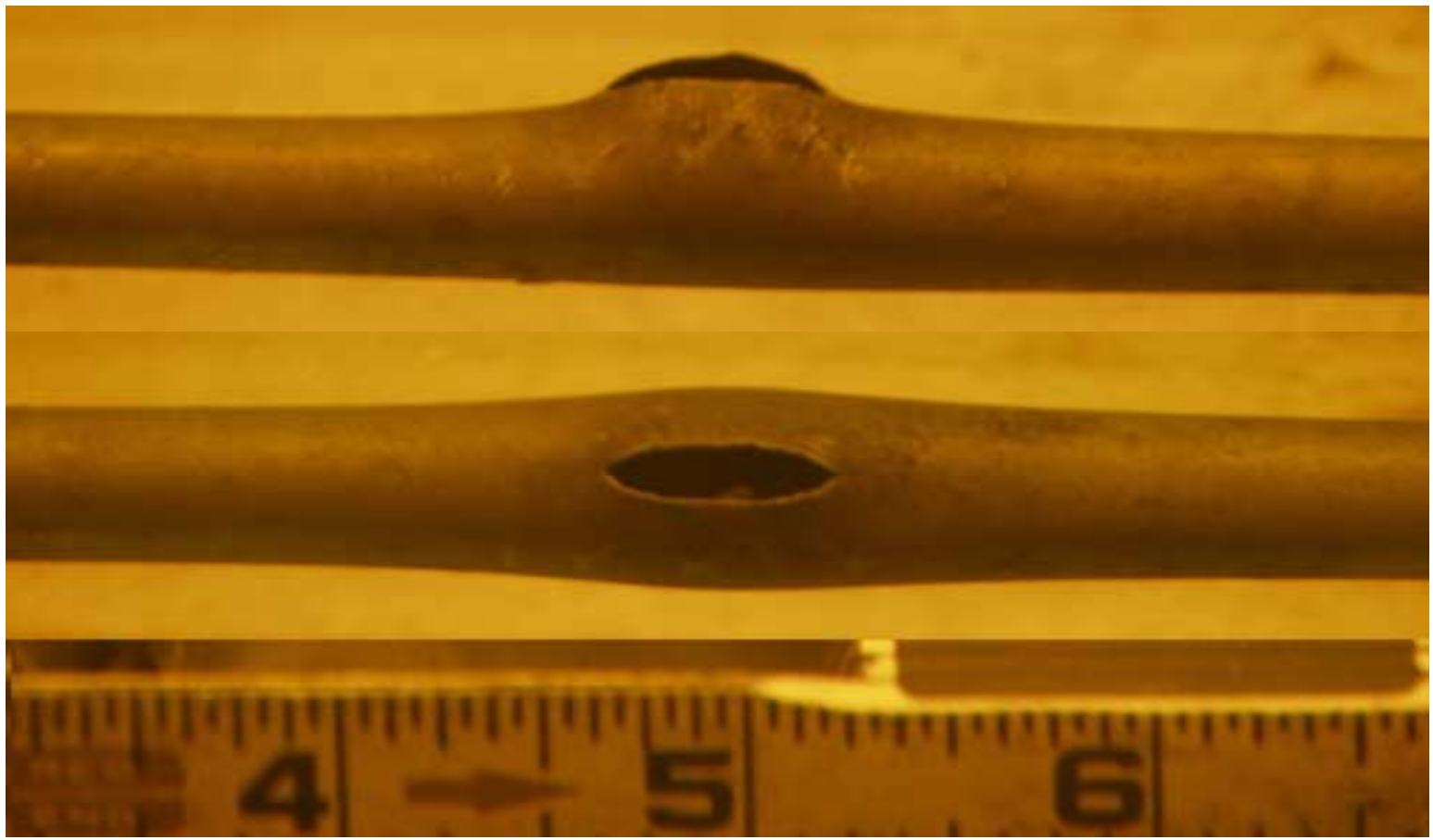
2nd LOCA INTEGRAL TEST RESULTS HIGH-BURNUP BWR PHASE B (Cont'd)

- **Ballooning**
  - Axial extent ≈100 mm, peak at 25 mm below midplane
  - Max. ΔD/Do = 50%; max. average strain = 40%
  - Uncorrected for oxide thickness
- **Burst Opening**
  - Oval-shaped
  - 14-mm long; 3.5-mm maximum width

2ND LOCA INTEGRAL TEST WITH HIGH-BURNUP BWR ROD: PROFILOMETRY



LOCA INTEGRAL TEST (PHASE B)
HIGH-BURNUP BWR BALLOON & BURST



FUEL BEHAVIOR DURING AND AFTER HIGH-BURNUP BWR LOCA TEST #2

- **Dark Deposit on Quartz Tube (same as in Test 1)**
  - Black deposit on tube (will be gamma-scanned, Cs??)
  - Occurred during burst; stable during steam oxidation
- **Fuel Particle Fallout during Post-Test Handling**
  - Fuel particles (<1 g) ejected during test were collected
  - Bottom of test train was capped to trap fuel fallout during transfer and handling
  - Total of 4 grams of fuel were collected
  - Fallout continues with additional handling

NEAR TERM LOCA WORK

- **Verify Specimen Preparation Techniques**

  - Six-inch “practice”sample; bottom of Test #1 sample

  - Metallographic examinations (6-inch sample completed)

- **Determine Composition of Dark Deposit on Quartz Tube (Gamma Scanning)**
- **Determine ECR, O_2 and H_2 Axial Distributions 5-min. Tests (in-cell & out-of-cell) at 1204°C**
- **Move Quench System In Cell and Run Full LOCA Sequence (→Jan. 2003)**